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ORIGINAL PAPER

Climate change mitigation through increased wood use in the European construction sector—towards an integrated modelling framework

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Abstract Using wood as a building material affects the carbon balance through several mechanisms. This paper describes a modelling approach that integrates a wood product substitution model, a global partial equilibrium model, a regional forest model and a stand-level model. Three different scenarios were compared with a business-as-usual scenario over a 23-year period (2008–2030). Two scenarios assumed an additional one million apartment flats per year will be built of wood instead of non-wood materials by 2030. These scenarios had little effect on markets and forest management and reduced annual carbon emissions by 0.2–0.5% of the total 1990 European GHG emissions. However, the scenarios are associated with high specific CO_2 emission reductions per unit of wood used. The third scenario, an extreme assumption that all European countries will consume 1-m^3 sawn wood per capita by 2030, had large effects on carbon emission, volumes and trade flows. The price changes of this scenario, however, also affected forest management in ways that greatly deviated from the partial equilibrium model projections. Our results suggest that increased wood construction will have a minor impact on forest management and forest carbon stocks. To analyse larger perturbations on the

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demand side, a market equilibrium model seems crucial. However, for that analytical system to work properly, the market and forest regional models must be better synchronized than here, in particular regarding assumptions on timber supply behaviour. Also, bioenergy as a commodity in market and forest models needs to be considered to study new market developments; those modules are currently missing.

Keywords Climate change mitigation · Integrated modelling · Wood substitution · Forest economics · Forest management · Wood construction

Introduction

In order to mitigate climate change, there has been growing interest in finding efficient ways to use biomass to substitute fossil fuels and non-biomass materials. Increasing the use of wood in construction has been seen as an important option for that. Using wood as a building material affects the carbon balance through at least four mechanisms: the relatively low fossil energy needed to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions from e.g. cement manufacture; the increased availability of biofuels from biomass by-products that can be used to replace fossil fuels; and the physical storage of carbon in wood building materials.

A growing body of knowledge supports that using wood-based material results in lower energy use and CO_2 emissions compared with other materials such as concrete, brick or steel (Koch 1992; Buchanan and Honey 1994; Buchanan and Levine 1999; Börjesson and Gustavsson 2000; Pingoud and Perälä 2000; Lippke et al. 2004; Gustavsson and Sathre 2006; Petersen and Solberg 2002, 2003, 2004, 2005; Pingoud et al. 2010; Sathre and O'Connor 2010). Gustavsson et al. (2006) compared the net CO_2 emissions from the construction of concrete- and wood-framed buildings and found that the most important contributor to the lower CO_2 balance was the recovery of wood residues, including logging, processing, construction and demolition wastes, for use as biofuel to replace fossil fuels. The results are in line with the analysis of carbon stocks and flows in trees, soil, wood products, and substitutable materials and fuels by Eriksson et al. (2007a), who found that overall carbon emissions were lowest when forests were managed intensively to produce construction materials. The mean forest carbon stock was slightly higher under intensive management than under traditional management but had a relatively minor effect on the overall carbon balance. The substitution effect of using wood instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues for use as biofuel led to avoided fossil emissions that were 7–10 times greater than the reduced soil carbon stock.

The CORRIM consortium (e.g. Perez-Garcia et al. 2005) also analysed management alternatives for individual forest stands taking into account the whole life cycle from forest growth to wood products used in buildings. They found that management strategies with shorter rotation lengths, higher biomass yields, but also lower forest carbon stock gave the best overall greenhouse gas benefits. Pingoud et al. (2010) analysed the impacts of various forest management strategies on both carbon stocks and substitution. The supplies of sawnwood, pulpwood and energy wood were given as input to estimate the impacts on emissions and carbon stocks of replacing concrete-frame buildings with wood-frame buildings. They found that the quality of the wood produced (saw logs, pulpwood, energy wood) had a substantial impact on the substitution potentials. Some fossil carbon displacement factors were greater than one, implying that relative emission reduction was larger than the carbon content of the wood itself. Consequently, maximizing the biomass production does not necessarily lead to the maximum substitution benefits, which also depends on the type of substitution.

Managing forest stands to achieve increased wood substitution or carbon sequestration in forests could result in silvicultural guidelines that differ from the current practices. Pohjola and Valsta (2007) suggested that increased carbon sequestration in forests is achieved by increasing growing densities and rotation length. Their analysis, however, did not consider the use of wood as a substitute for energy-intensive materials and fossil energy. Taking substitution into account will typically change the optimum timber assortment composition and the rate at which carbon is passed through the forest ecosystem (Valsta 2007; Raymer et al. 2009).

Several studies have analysed forest management and greenhouse gas mitigation on a regional or global level. At the regional scale, Hoen and Solberg (1994, 1999) showed that incorporating the value of carbon storage into forest planning affects forest management by e.g. changing clear felling priorities as well as increasing silviculture investments. Backéus et al. (2005) showed that harvest levels tend to decline as the price for carbon storage increases, an effect that is more pronounced in areas with lower production. However, they did not link the price for carbon with the value of bioenergy. Raymer et al. (2009) connected forest planning with climate change mitigation impacts of forest and forest products use in a model where all main elements in the carbon cycle are included and showed e.g. that substitution gives shorter rotation, higher planting densities and slightly more thinnings compared

with not including substitution. Taverna et al. (2007) examined the impacts of different forest management and wood use strategies on carbon sinks and emissions for Switzerland. They conclude that the growing stock of forests should first be increased to the level that may be accounted for in the Kyoto Protocol, and after that, one could start to use extra wood for long-lived wood products and for energy. Hoen and Solberg (1994, 1999), Backéus et al. (2005) and Raymer et al. (2009) included forest management endogenously, i.e. considered several forest management options simultaneously letting the actual choice of management be influenced by economic factors, whereas Taverna et al. (2007) calculated the global effects based on a given activity level.

In this study, we analyse the greenhouse gas implications of increased wood use in the construction sector. For this purpose, we develop a new approach of integrated modelling. We combine models for wood substitution in building construction, for forest product markets, and for forest management. Our objectives are (i) to study the CO_2 mitigation effects of increased wood use in Europe under different scenarios and (ii) to investigate the consistency of the linkages between the models of the system and discuss future improvements. One of our starting points is that as the demand for construction wood increases, this raises the demand for sawlogs. With increased production of sawnwood, the supply of residuals from the mechanical forest industry becomes more abundant. All this could affect the whole forest sector system all the way down to the forest manager, although the magnitude of these changes is hard to predict a priori. Furthermore, these interactions may vary in time as well as in space, over national submarkets.

The remainder of the article is organized as follows. The integrated modelling system is described in the next section. After that, the four demand scenarios for wood-based construction materials are presented. The results from the scenario analyses are presented thereafter. Following this, the results are discussed in broader context and the strengths and weaknesses of the analysis are considered.

Method: integrated modelling system

Four scenarios of increased wood use in the construction sector are considered. The system for analysing them includes (i) a model for wood substitution in building construction (ii) a global forest sector model (iii) a forest regional model and (iv) a forest stand model. Fig. 1 presents the models and their linkages.

Based on the scenarios for increased wood construction, we derive reference demand projections for sawnwood and panels from the wood substitution model and econometric studies. These projections are used as input in a global forest sector model (EFI-GTM) to produce the market equilibrium prices and volumes for roundwood and forest industry products. The market-adjusted demand for wood products is fed into the substitution model to assess the impacts on the carbon balances due to the substitution of fossil fuels and materials as well as the storage of carbon in wood products. The market prices are further input into a forest model for Sweden (SMAC) in order to study the resulting forest activities of a larger region and assess the changes in forest carbon stock over time. A stand-level model (SMA) is used for a detailed study of the

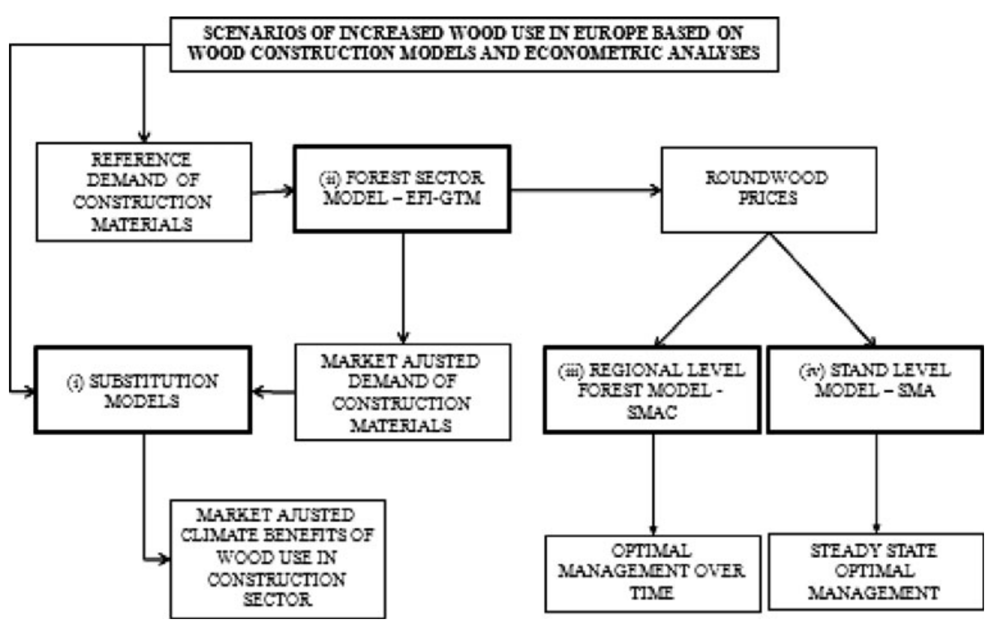

Fig. 1 The information flow between models

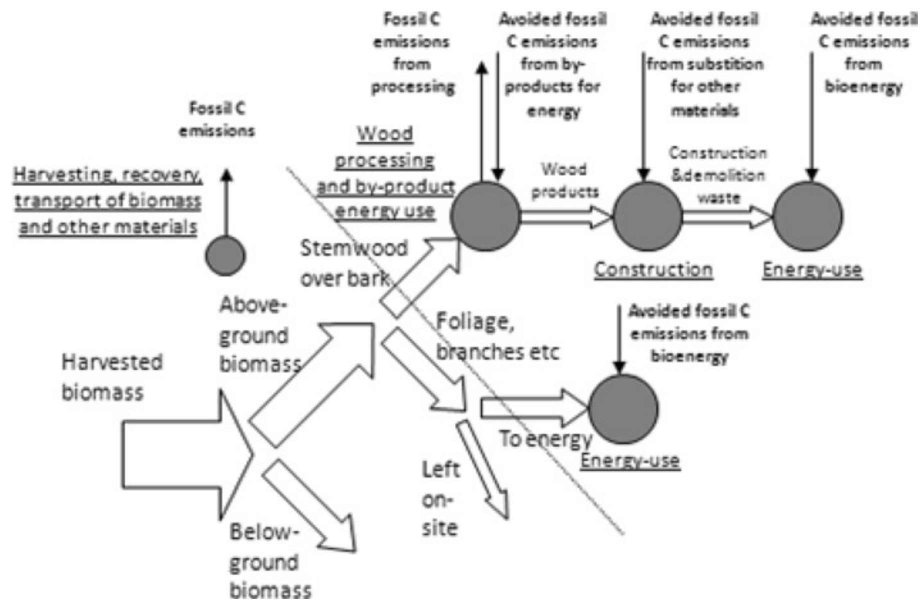

Fig. 2 Description of wood-use chains in the substitution model

implications of the timber prices for forest management, long-term timber supply and average carbon storage in forests. All the individual models have been used and fully described in other studies; thus, we describe them only briefly below.

(i) Substitution model

In the model for wood substitution in building construction, the model inputs are the amounts of building materials needed to build a wood-framed building and a reference building made mainly with non-wood materials. The outputs are (1) the reduced net carbon emissions due to producing wood building materials instead of non-wood building materials (2) the avoided fossil carbon emissions from using as bioenergy the additional biomass residues when wood building material is used instead of non-wood and (3) the additional amount of tree biomass needed to produce the wood building materials. A schematic framework of the substitution model is shown in Fig. 2.

The CO_2 balance includes emissions from fossil fuel combustion for material processing and logistics, the reduction in emissions due to replacing fossil fuel with biomass residues, the avoided emissions due to cement process reactions and the carbon stock change in wood materials. As we consider all biomass flows associated with the building construction to be part of the system, the biomass residues from the harvest, processing and demolition that are available for use outside of the production process are assumed to be used to replace fossil fuel. The calculated material and energy substitution effects are limited to those from the additional biomass harvested and do not include substitution benefits from baseline wood harvests. In this analysis, the reference fossil fuel is coal, meaning that the biofuel replaces coal fuel, and electricity used for material production comes from coal-fired condensing plants. The substitution modelling is described in more detail by Gustavsson et al. (2006), Gustavsson and Sathre (2006) and Pingoud and Perälä (2000).

(ii) Forest sector model—EFI-GTM

The global forest sector model links forest resources, wood supply, forest industry production and the market demand for forest products in 55 regions, with nearly all of the European countries each modelled as a separate region and including trade between the regions for each product. Simulating competitive markets using the approach by Samuelson (1952), the model solves for supply, demand, trade and prices for forest sector products in each region and time step. The model is documented in Kallio et al. (2004), and its recent applications include e.g. the study by Kallio et al. (2006), Moiseyev et al. (2010) and Solberg et al. (2010).

(iii) Forest regional model—SMAC

In the forest regional model, simulations for forest growth are made for sample plots from the Swedish National Forest Inventory. Simulations of silvicultural and harvesting activities over time are built on the assumptions that forest owners are maximizers of net present value and that they have myopic price expectations, i.e. when they make their decisions in each 5-year period, they expect that the current price level (and other economic conditions) will persist through time. The SMAC model is built on the

Table 1 Share of wood construction in one- and two-family house construction and per capita consumption of sawn softwood, in selected countries or regions

Country	Share of wood construction (%)	Sawnwood, per capita consumption in 2006[e]
USA	90–94[a]	0.34
Canada	76–85[a]	0.58
Nordic countries	80–85[a]	0.63
Scotland	60[b]	–
United Kingdom	20[c]	0.16
Germany	10[a]	0.24
The Netherlands	6–7[d]	0.15
France	4[b]	0.17

[a] HAF (2000)

[b] Reid et al. (2004)

[c] Toratti (2001)

[d] Kuilen (2001)

[e] Faostat (2008) and Hänninen (2008)

dynamics of the forest model by Sallnäs (1990). It is an area matrix model that distributes the forest on some 10,000 states. The model operates with 5-year periods, in contrast to the 1-year period of the EFI-GTM model. A recent application is found in the study by Eriksson et al. (2007b). From the state of the forest in each 5-year period, the carbon stock sequestered in the forest is deduced. Changes in soil/ground-based deposits are not accounted for.

(iv) Stand-level model—SMA

The stand-level model examines how optimum silviculture practices would depend on the wood prices identified in the scenarios. In other words, it considers how profit maximizing forest owners would behave in the long run in a new economic environment with changed wood prices. Because of the nature of the stand-level model, the economic parameters such as wood prices are kept constant over the rotation. The SMA model was developed for the optimization of the forest management at the stand level and uses non-linear, non-differentiable optimization (Hooke and Jeeves 1961) to find the optimum thinning and rotation solutions (Valsta 1992; Pohjola and Valsta 2007). The results give economically optimal stand development, i.e. thinning timing and intensity, rotation length, as well as average total volume and amounts of pulp wood and logs per hectare over the rotation. The maximization of soil expectation value was used as objective function. Under economic regularity assumptions, the solutions lead to the maximization of the forest owner's wealth considering an infinite time perspective (Johansson and Löfgren 1985).

Scenarios

The amount of wood used in building construction varies significantly across Europe. Table 1 shows that the share of wood for constructing one- and two-family houses is rather low in Europe, except in the Nordic countries. Wood is commonly used in Nordic countries for single-family houses but is less common in multi-storey apartment buildings. In contrast, wood is commonly used in North America for the construction of both single-family and multi-storey apartment buildings. In recent years, wood has shown signs of increased market penetration in many European countries. The apparent consumption (production+imports−exports) of sawn softwood was about 0.2 m^3 per capita in the European Union in 2006, whereas it is about 1.0 m^3 per capita in Finland and the average in the Nordic countries is 0.6 m^3 (see Table 1) (Hänninen 2008). The number of apartment flats completed annually in the 19 European countries in the Euroconstruct statistics was on average 1.2 million during 2003–2005 (Euroconstruct Conference 2006).

Apparently, there is a large potential to increase the use of wood as a construction material. We consider three scenarios named *Sweden*, *Finland* and *1m3cap*, where the use of wooden materials is assumed to significantly increase in building construction. In addition, a baseline scenario (*Base*) is created to depict the business-as-usual case, in order to compare the implications of the scenarios with the present development. Each scenario yields the assumed reference volumes of construction material that are used as input in the EFI-GTM model, which produces market-consistent volumes and prices, which subsequently are applied in the other models. The scenarios are characterized as follows:

- *Base*: "Business-as-usual" corresponding to a growth rate of total European sawn softwood consumption estimated to be slightly below 1% annually up to 2030.
- *Sweden*: Wood is used instead of conventional concrete construction for building apartment blocks in Europe, gradually increasing to 1 million apartment flats per year above the *Base* scenario by 2030. The construction data are from a case study of a building constructed in Växjö, Sweden.
- *Finland*: The same as case *Sweden*, but using construction data from a case study of a building in Helsinki, Finland.
- *1m3cap*: Consumption of sawn softwood in all European countries reaches 1 m^3 per capita by 2030, corresponding to a growth rate of about 7% per year in Europe.

In the *Base* case, the reference consumption for forest industry products (except for sawn softwood) from 2008 to

2030, given the current prices, is defined applying the existing assumptions accommodated in the EFI-GTM model. For sawn softwood, the reference demand is created using statistical smoothing methods for the available country-specific time series accounting for the past per capita consumption and population forecasts (Hänninen 2008).

The difference between the scenarios *Sweden* and *Finland* is the type of wood construction and the type of reference concrete construction replaced. Scenario *Sweden* uses data from a case study of the Wälludden building constructed in Växjö, Sweden (Gustavsson et al. 2006). This is a 4-storey building containing 16 apartments and a total usable floor area of 1,190 m^2. Scenario *Finland* uses data from a case study of a 4-storey apartment block built in 1997 in the ecological building area of Viikki in Helsinki, Finland (Gustavsson et al. 2006). The building contains 21 apartments with a total usable floor area of 1,175 m^2. In the scenarios, the results of micro-level case studies of individual multi-storey houses are scaled up to macro-level to give projections of the additional demand for sawnwood, plywood and particle board in excess of the baseline development. Because the diffusion of construction innovations will take time (Mahapatra and Gustavsson 2008), we assume that the use of wood in multi-family housing increases linearly from 2008 to 2030. The flats will be allocated across the European countries in proportion to the building volumes in 2003–2005 (Euroconstruct Conference 2006). Seventy percent of harvest residues, 100% of processing residues that are not used internally, 100% of construction site waste and 90% of demolition waste are assumed to be used as bioenergy to replace coal.

In scenario *1m3cap*, the annual per capita consumption of sawnwood is assumed to reach 1.0 m^3 per capita by 2030 in all European countries. In this scenario, the substitution impact of increased wood use is estimated using displacement factors calculated for sawnwood, based on a study by Pingoud and Perälä (2000), in which 1 kg of wood-based building materials substitutes for 3.6 kg of masonry products (concrete, bricks, tiles) and 0.12 kg of metals, instead of the building-level substitution data of Gustavsson et al. (2006). The demand for other forest industry products is assumed to develop as in the baseline. This is a very extreme scenario, which was created primarily to study the integrity of the linkages between the

Table 2 Projections for production and consumption of forest industry products in EU/EFTA region

Scenarios	Growth of consumption, p.a., Average 2008–2030 (%)	Growth of production, p.a., Average 2008–2030 (%)	Consumption 2030[a]	Production 2030[a]	Change in consumption to *Base* in 2030[a]	Change in production to *Base*, 2030[a]
Sawn softwood						
Base	1.0	0.1	123	102		
Sweden	1.1	0.2	127	103	4	1
Finland	1.3	0.3	133	107	10	5
1m3cap	5.7	3.1	417	213	294	111
Other mechanical forest industry products						
Base	0.9	1.2	101	87		
Sweden	0.9	1.2	102	87	1	0
Finland	1.1	1.3	104	89	3	2
1m3cap	1.1	2.4	106	113	5	26
Chemical pulp						
Base	0.5	1.0	28	31		
Sweden	0.5	1.0	28	31	0	0
Finland	0.5	1.0	28	31	0	0
1m3cap	0.6	1.2	29	32	1	1
Paper and paperboard						
Base	1.3	1.0	128	117		
Sweden	1.3	1.0	128	117	0	0
Finland	1.3	1.0	128	117	0	0
1m3cap	1.3	1.1	128	121	0	4

[a] Units are million m^3, for sawn softwood and other mechanical forest industry products, and million tonnes for chemical pulp and paper and paperboard

different models of the system. It also serves the purpose of illustrating the scale of effects for such a consumption level.

Results of the scenario analyses

The scenarios outlined above were input into the EFI-GTM model. In the EFI-GTM, the regional demand functions for the forest industry products are modelled to shift annually in response to the consumer income (GDP)-induced "business-as-usual" change in demand, as well as the additional scenario-dependent demand increase component (zero in the baseline). The demand functions are downward sloping, subject to price elasticities from econometric studies. The model equilibrates simultaneously the demand and supply of all commodities including roundwood and chips through market prices. Hence, the eventual market-adjusted demand for the various forest industry products depends on the market prices and is not necessarily equal to the above-defined reference demand in any of the scenarios. The resulting consumption of wood products is input to the substitution model to evaluate the changes in carbon balance in the construction sector, whereas the roundwood prices are used to address the changes in forest management by the SMAC and SMA models. Here, we summarize the results in the same order, beginning with roundwood demand and prices, followed by substitution emission reductions, forest regional model results and the stand-level steady-state analysis.

Table 3 Changes in Swedish roundwood prices in the alternative scenarios in 2030, with respect to the *Base* case (%)

	Sweden	Finland	1m3cap
Softwood sawlogs	2.7	5.2	110
Hardwood sawlogs	0.1	0.2	0.6
Softwood pulpwood	0.3	0.3	−19
Hardwood pulpwood	0.2	0.2	−9

Roundwood demand and prices

Table 2 shows the projected development of consumption and production of mechanical forest industry products in Europe, for the four scenarios. The global market impacts of the assumed increase in wood consumption in the construction sector are rather minor in scenarios *Sweden* and *Finland* when compared with the baseline. In all the three scenarios, forest product demand increases more than production in Europe, and part of the growth in wood products consumption in the construction sector is satisfied by imports.

Expectedly, greater changes in comparison to *Base* occur in the very extreme scenario *1m3cap*. The sawn softwood consumption was assumed to rise to 475 million m^3 in 2030, so that each European would use 1 m^3 of sawnwood annually. The actual market-adjusted consumption met by the globally increasing sawnwood production increased to 417 million m^3 in 2030. The rise in timber costs made it unprofitable for the industry to expand more, despite the sawnwood price increase. Roughly 60% of the demand increase in Europe was satisfied by imports. Furthermore, part of the sawnwood consumption outside Europe (35 million m^3 in 2030) was redirected to Europe.

Regarding the Swedish forest sector, there are differences mainly between the scenario *1m3cap* compared with the other scenarios. The differences between the scenarios *Base, Sweden* and *Finland* are small; both the harvests and use of roundwood are about 78–79 million m^3 in Sweden in 2030 in these scenarios. In 2030, the difference in softwood lumber production between the scenarios *Base* and *1m3cap* is about 7 million m^3, which leads to an increase in sawlog harvest of about 14 million m^3. Because the increased supply of sawmill chips causes a decline in demand for the substitute product, pulpwood, the total harvest increases only some 9 million m^3.

Table 4 Increase in annual reference and market-adjusted roundwood consumption in European markets (EU, Norway and Switzerland) and globally, and C emission reductions due to wood substitution (not including changes in forest stock), in scenarios *Sweden*, *Finland* and *1m3cap* in comparison to *Base*, in 2030

	Increase in demand for roundwood (million m^3 per year)			Reduction in C emission (million tC per year in the year of construction)		
	Sweden	Finland	1m3cap	Sweden	Finland	1m3cap
Reference increase (based on scenario assumption of demand drivers)	9.7	23.8	598.6	4.3	9.7	202.3
Market-adjusted increase directed to European markets	9.1	22.6	487.8	4.0	9.2	164.8
Market-adjusted global net increase	7.2	18.3	429.5	3.2	7.5	145.1

Table 3 compares the price changes in scenarios *Sweden, Finland* and *1m3cap*, with respect to the *Base* case in Sweden in 2030. The *Swedish* case has the lowest market impacts, with softwood sawlog price being about 3% up from the *Base* case level in 2030. In *1m3cap*, the sawlog price more than doubles from the *Base* case due to the drastically increased softwood lumber demand. The growth in sawn softwood production makes sawlog chips supply abundant and leads to decline in the pulpwood harvests and price. In scenario *1m3cap*, the softwood pulpwood price comes down by close to 20% compared with *Base* in 2030. Due to the substitution effect in panel production, the hardwood pulpwood price also falls. However, we did not consider the effects of bioenergy markets and their potential competition for pulpwood and chips. Had bioenergy demand been considered, the prices of pulpwood and sawmill chips might have decreased less than they did in *1m3cap*. However, higher sawmill chips prices would have simultaneously improved the profitability of the sawnwood industry and further increased its output, driving the sawlog demand and prices still further up. Still, the net effect would probably be that the relative difference between the sawlog and pulpwood prices would not grow as wide as in *1m3cap*.

Emission reductions from construction

Table 4 gives the reference and market-adjusted emission reductions due to increased wood-use scenarios with respect to the baseline in the year 2030. The calculations exclude the changes in carbon stored in the forests. The calculations are subject to many assumptions and uncertainties, which are discussed more closely below.

If one million additional flats of the Swedish design were made annually with wood frames instead of concrete frames (scenario *Sweden*) by 2030, the carbon emission during the year of construction would be reduced by 4.3 million tC. Of this emission reduction, 24% derives from reduced fossil fuels used for material production, 27% comes from reduced cement process reaction emission, 32% comes from increased substitution of fossil fuels by biomass residues and 17% comes from increased carbon storage in building materials. Over the complete life cycle of the buildings produced each year, the carbon emission reduction would be 4.2 million tC. Of this, 25% is from fossil fuels for material production, 25% is from cement process reactions and 50% is from fossil fuel substitution. Over the complete life cycle of the buildings, there is no permanent emission benefit due to carbon storage in building materials, but by 2030, this carbon stock will still remain in the buildings.

In scenario *Finland*, the respective emission reduction would be 9.7 million tC compared with the concrete alternative. The difference between scenarios *Sweden* and *Finland* highlight the importance that the building design (of both the wood building and the reference building it is assumed to substitute for) has on wood demand and thereby on C emission reduction.

In the market simulations, the assumed demand increases in scenarios *Sweden* and *Finland* are largely met. Hence, the market-adjusted reductions in carbon emissions are similar to the reference reductions based on scenario assumptions.

In the market simulation of scenario *1m3cap*, only about 80% of the reference demand (1 m^3 per capita) for sawn softwood materializes, rendering a corresponding reduction in carbon emission of about 165 Mt C per year (Table 4). As this increased sawnwood demand would reduce the consumption outside Europe compared with the baseline, the overall reduction in carbon emissions would be less. The figure does not account for the changes in carbon sequestered in forests, although the increase in imported roundwood and sawnwood needed to satisfy the European demand would have effects on the growing stocks of forests globally. Finally, it must be kept in mind that the assumed substitution impacts characterize new construction, whereas in reality, a substantial share of the increased use of sawnwood in scenario *1m3cap* would go to other uses, e.g. to renovation where demolished wood is replaced by new wood. Hence, the figures are likely to be overestimates.

Expressed in units of C emission reduction per unit of C in additional harvested roundwood, the *Sweden*, *Finland* and *1m3cap* scenarios achieve emission reductions of 2.22, 2.04 and 1.69, respectively. In units of C emission reduction per unit of C in additional wood products, the respective emission reductions are 4.17, 3.83 and 3.45. In a meta-analysis of carbon displacement factors of wood

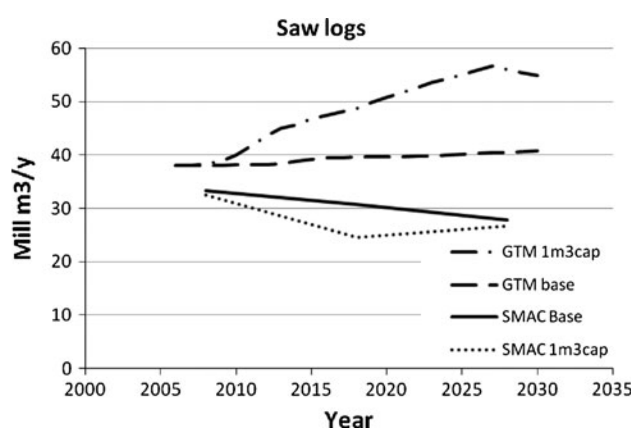

Fig. 3 Sawlog harvest volumes from EFI-GTM and SMAC under different demand scenarios over the first 3 10-year periods (data points are for each year for EFI-GTM and for years 2008, 2018 and 2028 for SMAC)

product use, Sathre and O'Connor (2010) found a wide range of C emission reduction per unit of C in wood products, from a low of −2.3 to a high of 15, with an average value of 2.1. The carbon displacement depends on the characteristics of the wood building and the reference non-wood building, the amount of wood residues recovered for use as biofuel, the fossil fuel that is substituted by the recovered biofuels and the fate of the wood material at the end of the building life cycle. The scenarios analysed in this study represent relatively efficient use of wood products for climate change mitigation, and the efficiency varies between the scenarios. As the price of carbon emissions or fossil fuels increases, one would expect the demand for more efficient wood substitution to increase. This could be achieved through alternative building design (e.g. scenarios *Sweden* vs. *Finland*), increased recovery of biomass residues, and using recovered residues to replace fossil fuels with greater carbon intensity.

Forest regional model analysis

The price series for the years covered by the EFI-GTM for scenarios *Base* and *1m3cap* were converted to 5-year averages to comply with the time step of the SMAC model (scenarios *Sweden* and *Finland* were not analysed as they give results similar to *Base*). Volumes are presented by 10-year periods because the initial two 5-year periods reveal an adjustment pattern that makes comparisons difficult. A discount rate of 2.5% p.a. is assumed.

Figure 3 shows the harvest of sawlogs projected by the SMAC model and the EFI-GTM. Two observations can be made. First, the sawlog volumes given by the SMAC volumes are about 20% smaller than the EFI-GTM volumes in the first 10-year period. What is more conspicuous is that in the following periods sawlog volumes decrease in SMAC, whereas they increase in EFI-GTM. Furthermore, the harvest volumes in SMAC are smaller in the *1m3cap* scenario than in the *Base* scenario despite a higher price increases in the former.

There may be several explanations to this. Since relatively more sawlogs are on average extracted in final felling compared with thinning, one would expect that relatively more comes from final felling with an increased sawlog price. However, in the second 10-year period, thinning as a fraction of total harvests is instead increased compared with the first period in scenario *1m3cap*. The high gap in the sawlog and pulpwood prices, which is in fact increasing by about 3% p.a., may make it profitable to (i) postpone final harvests to get higher sawlog volumes in stands which are ready for final fellings and (ii) to take out more pulpwood in thinnings because the thinned stands provide larger sawlog volumes in the later final fellings. This reduces total harvest and increases thinnings in SMAC. Thus, the seemingly counterintuitive results of the *1m3cap* scenario are, at least partly, explained by prolongation of the rotation period that creates a temporary reduction in timber volumes that cannot be met by increased thinnings.

It must also be noted that SMAC looks, in each time period, for the optimal forest management and roundwood supply given exogenous prices that are assumed to prevail indefinitely. SMAC does not include roundwood demand. In the EFI-GTM, demand and supply are required to balance, as the model focuses on finding the market equilibrium. In the EFI-GTM, the timber supply functions are exogenous and tied to timber supply and volume elasticities aiming at reflecting the aggregated behaviour of the forest owners, as estimated in the econometric studies. The results of the studies mirror the facts that non-timber values also affect the forest management decisions and that the forest owners face uncertainty over the long-run persistence of any price levels observed as the markets are highly cyclical. Hence, they may tend to offer sawlogs to the markets when the prices are high, instead of postponing the sales in order to get even higher stumpage income in the future. Nevertheless, the steadily increasing sawlog prices would also gradually change the forest management as described by SMAC.

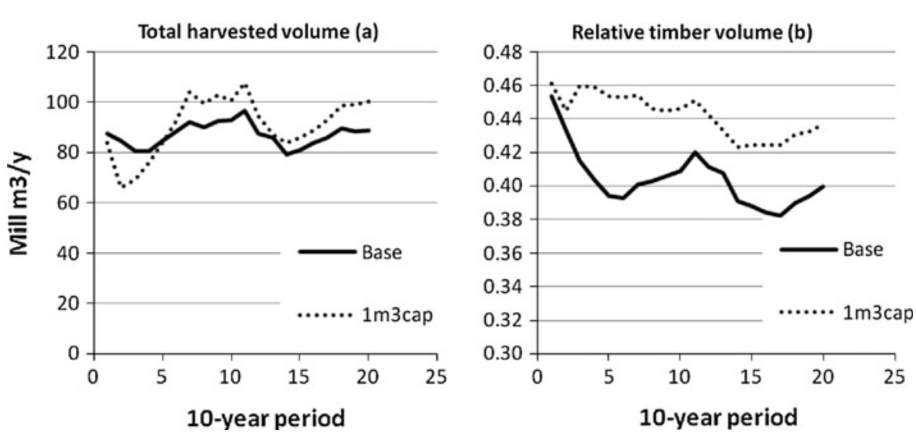

Fig. 4 Volumes of (**a**) total harvest and (**b**) the relative share of timber of the total harvest, over 200 years for *Base* and *1m3cap* scenarios with the SMAC model

The above explanations are strengthened by the long-term projection shown in Fig. 4. It assumes that the price level of year 2030 is maintained for the remaining part of a 200-year period. The initial drop in total harvests over the first decades in scenario *1m3cap* results in high removals in years 70–110. Except for the first two decades, the relative share of thinning out of the total harvest is about 10% higher in *Base*. The prolonged rotation period and reduction in thinning result in relatively more timber in the long run.

The figures for forest carbon stock in Sweden are not reported here since the harvested volumes differ so much from those of the EFI-GTM that the calculated changes in carbon stock have no effective relation to the emission reductions from construction.

Stand-level steady-state analysis

The stand-level analysis examines how the optimum steady-state silviculture practices of the forest owner would change as a response to new prices. Prices from the EFI-GTM model for year 2030 for the scenarios *Base* and *1m3cap* are applied, as they take into account the long-term impacts on the forest sector (the price difference between scenario *Base* and scenarios *Sweden* and *Finland* is too small to be of interest). The price for coniferous sawlogs is 50.3 €/m^3 and for coniferous pulpwood 35.7 €/m^3 in the *Base* scenario. In the scenario *1m3cap,* the corresponding prices are 105.5 and 29 €/m^3. These prices are road-side prices including bark. Compared with the *Base* case, the price for coniferous sawlogs thus increases by 110%, while the price for coniferous pulpwood decreases by 19%. A discount rate of 3% p.a. was used (2.5% for the forest regional model). The results of the optimization process are dependent on assumptions about discount rate and other model parameters. Also, the model structure does not consider demand for bioenergy, which affects the results.

For spruce-dominated forests, stand-level analyses were made for both high fertility Oxalis-Myrtillus type (OMT) and medium fertility type (MT) sites (Cajander 1949) by using two plots measured in southern Finland. For Scots pine, computations were performed for three plots. One of them represents the MT site type and two the less fertile, VT site type. For both price alternatives (*Base* and *1m3cap*), computations were made by varying the number of thinnings. Additionally, the young stand density (number of established seedlings) was optimized for each analysis.

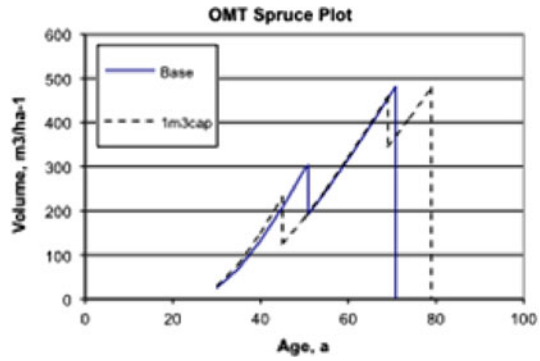

Fig. 5 Optimal timing of thinnings and rotation length at a OMT Norway spruce stand, for the *Base* and *1m3cap* scenarios

The change in prices predicted by the EFI-GTM model causes a significant change in the optimal treatment schedule for spruce-dominated stands, especially for the most productive stand type (Table 5). The change in the price extends the rotation by 8 years, increases the optimal number of thinnings from one to two, scales up optimal planting density and increases both the average volume and the production of sawlogs per hectare and simultaneously decreases the production of pulpwood. Compared with the *Base* scenario, in the *1m3cap* scenario, the first thinning occurs several years earlier (Fig. 5). A second thinning becomes optimal and takes place 10 years before the final felling.

For the spruce stand belonging to medium fertility class (MT, *Myrtillus* type), changes are somewhat smaller: for both the *Base* and *1m3cap* scenarios, a one-thinning option is optimal and the price change does not increase the optimal planting density. A change in price relation causes only a slight increase in average volume (2 m^3/ha) and a small decrease in the yield of pulp wood (0.1 m^3/ha-yr) but does not change the average yield of saw logs, even though the rotation age is lengthened by 6 years.

For Scots pine, the effects are also somewhat different among plots and fertility classes. For two plots, the

Table 5 Optimum silviculture in Norway spruce stand for the scenarios *Base* and *1m3cap* for site class OMT (high fertility)

Scenario	Number of thinnings	SEV € (ha^{-1})	Average volume (m^3 ha^{-1})	Annual yield m^3 (ha^{-1}a^{-1})	Sawlog yield m^3 (ha^{-1}a^{-1})	Pulp wood yield m^3 (ha^{-1}a^{-1})	Established stand density trees (ha^{-1})	Rotation length, a
Base	1	2,256	139	8.4	4.5	3.8	2,069	70.8
1m3cap	2	3,928	162	8.8	5.1	3.6	2,416	78.9
Difference	1	1,672	23	0.4	0.6	−0.2	348	8.1

optimum number of thinning increases from four to five. Rotation age is increased by 4–7 years for these plots. For the third plot, rotation length is shortened and the number of thinnings remains unchanged. It should be noted that net present value is quite similar for three to five thinnings, especially in the *Base* case. For all plots, thinnings take place earlier in the *1m3cap* scenario in order to increase the amount of sawlogs over the rotation. The annual yield of Scots pine sawlogs is increased modestly by 0.1–0.7 m^3/ha-yr. On the other hand, the yield of pulpwood is decreased by 0.3–0.7 m^3/ha-yr. Thus, the impact on total supply varies from slightly negative to slightly positive.

Impacts on average volume, and thus the average carbon stock in standing biomass, over a rotation also vary between plots. For two Scots pine plots, representing VT type, the carbon stock is 1.1–1.4 tC/ha lower in scenario *1m3cap*. On the other hand, for more fertile Scots pine stand, the average carbon stock is increased by 3.3 tC/ha in scenario *1m3cap*. For the more fertile spruce stand, the increase is 2.6 tC/ha, while at the MT spruce stand the difference is minor. Overall, the impacts are quite small as the typical biomass in boreal forests is in the range of 50–150 tC/ha (Lehtonen et al. 2004). However, even in cases where the average volume is smaller but sawlog production increases, the total climate change mitigation effect may be positive due to material substitution with wood products manufactured from larger stems. As the time horizon under consideration lengthens, the cumulative substitution benefits outweigh the one-time change in average carbon stock in standing biomass.

Discussion and conclusions

The implications of increased wood use in building construction with regard to forest product markets, forest management and greenhouse gas emissions were addressed in this study. The global impacts of the increased demand for wooden construction material on the forest product markets were simulated with the EFI-GTM model. This gave us projections for sawlog and pulpwood prices, demand and supply in Sweden and globally up to the year 2030. The market-adjusted demand for wood building materials was used in a substitution model to determine the reduction in fossil carbon emissions. The prices were also used as an input in a regional forest model and a stand-level model to simulate the forest management and the resulting harvests at the country and stand level. Whereas the regional model could be characterized as a medium-term transition model, the stand model supplied long-run, steady-state results.

The scenarios *Sweden* and *Finland*, which are driven by the desire to construct 1 million apartment flats annually using wood materials instead of concrete materials, have relatively minor effects on European markets, forest management and carbon emission reductions. The emission reductions, however, were achieved efficiently with high specific CO_2 emission reduction per unit of wood used. The building design is shown to be quite important. The annual emission reduction from the construction sector (without changes in forest carbon stocks) above the "business-as-usual" development corresponds to about 0.2% (scenario *Sweden*) and 0.5% (scenario *Finland*) of the 1990 greenhouse gas emissions of EU27, Norway and Switzerland, which were about 5,667 Mt CO_2 equivalent (1,545 Mt carbon equivalent). A large part of the emission reduction was due to the substitution of fossil fuels by biomass. Hence, attaining these reductions would involve the energy sector as well. Over a longer time perspective, additional bioenergy can be obtained from demolition waste at the end of the buildings' life cycle (Sathre and Gustavsson 2006).

In the very extreme scenario *1m3cap*, where we assumed that the markets were driven by the desire for each European to use 1 m^3 of sawn softwood annually, the emission reductions would be considerably larger. Nevertheless, such reduction is very hard to estimate accurately, not only because the sawnwood consumed in the scenario would be directed to various end-uses with different greenhouse gas balances, but also because the high increase in European sawnwood demand would change the global forest products market considerably.

Given the roundwood prices projected for scenarios *Sweden* and *Finland*, there would hardly be any changes in forest management from the baseline practices as predicted by the SMAC forest regional model for Sweden and consequently, little change in the stock of forest carbon. With the larger price changes following scenario *1m3cap*, the SMAC model gives lower fellings in Sweden in the first 2–3 decades compared with the EFI-GTM results because of the reasons discussed in chapter 4. In short, this means that changes in forest carbon stock in scenario *1m3cap* cannot be followed over the transition period by SMAC. However, an increased harvest in productive forests, like those in Sweden, would most likely result in a reduction in carbon stock in the short term whereas the stand-level results presented here indicate that stocks could increase slightly in the long term.

The results from the stand-level model indicate relatively small changes in carbon stock from the business-as-usual case even with the drastic price changes in the *1m3cap* scenario. Sawlog output increases but is in most cases balanced by a similar reduction of pulpwood. Rotations are prolonged, and for several stand types, the number of thinnings is increased. Planting densities are generally increased. When the amount of sawlog output is increased,

the average carbon storage in the forest might slightly decrease for Scots pine in some cases. For spruce, however, it is possible that due to increasing demand of sawn wood, higher prices for sawlogs in relation to pulpwood could cause a transition towards continuous cover forestry with single tree selection cuttings and primary emphasis on log-sized wood production. This management strategy would simultaneously enhance the forest carbon stocks. These results are in agreement with those presented by Pingoud et al. (2010), Hoen and Solberg (1994, 1999) and Raymer et al. (2009), indicating that it is possible to increase both the average carbon stock in forests and the supply of saw logs by increasing the rotation length and basal area compared with current silviculture. As pointed out above, the increased rotation length in scenario *1m3cap* is also seen in the forest regional model of Sweden. Including bioenergy markets into the models, whether in EFI-GTM or SMAC, would probably have changed the results in *1m3cap* as it could have induced higher demand and increased prices for smaller wood dimensions and other assortments not suitable for sawnwood.

Concerning the integrated modelling framework, there are many options for improving the analysis in the future. Consistency between the construction scenarios and the EFI-GTM model is already built into the system as the result of the former being an assumption in the latter. In reality, one would also expect that there is a feedback loop between prices established at the timber markets back to the wood construction scenarios, but this interaction is not included in the current model system (cf. Fig. 1). However, in scenarios Sweden and Finland, the feedback would be minor as the influence on timber market prices compared with the base case scenario is very low.

With the forest regional model, the harvest levels for sawlogs deviated from those projected for Sweden by the EFI-GTM. The EFI-GTM is able to describe how much the sawlog prices increase due to the higher demand in the sawnwood industry and how pulpwood prices drop as a consequence of more sawmill chips streaming into the market. However, the supply of roundwood in the EFI-GTM is based on separable supply functions for pulpwood and sawlogs, neglecting the fact that also the relative prices between sawlogs and pulpwood should affect the supply. Such changes do affect forest management and supply in the forest models.

Another difference is the assumptions regarding timber supply behaviour, where the forest models assume perfect foresight of prices (like in SMA) or myopic price behaviour (like in SMAC in this application), whereas in EFI-GTM timber supply is based on econometric studies of short-run timber supply. Our results show that it is important to be aware of this difference.

For an internally consistent analysis of the optimal forest management and forest sector demand for roundwood, a dynamic optimization model like FASOM, with simultaneous demand and supply mechanism, would be useful. But also here one meets the problem of forest owner behaviour based on myopic or perfect foresight. Another option for improved consistency between various models and model levels would be to integrate SMAC, or a simplified version of it, and the EFI-GTM into the same model as exemplified by Sallnäs and Eriksson (1989). Introduction of the bioenergy sector into the modelling structure, which is desirable in its own right, is likely to complicate the harmonization of the models.

Between the SMAC regional model and the SMA stand model, a high degree of consistency could be observed. Higher sawlog prices relative to pulpwood implicate longer rotations and increased production of sawlogs in the long run. However, consistency could be increased by allowing for variations in planting density in the SMAC model, something which is not possible today and shown to be of importance by the stand-level model analyses.

In summary, our results suggest that increased use of wood in construction will have minor impacts on forest management and forest carbon stocks. For scenarios exemplified by *Sweden* and *Finland*, the need for an integrated modelling approach appears less motivated. For larger perturbations on the demand side of the forest product market, the inclusion of market clearing models seems crucial. Through them, the implications for forest management could also be quantified. However, for that to be accomplished reliably, the market and forest transition models must be better synchronized. Also, bioenergy as a commodity in market and forest models needs to be considered in order to broaden the range of potential market developments that could be analysed (Gustavsson et al. 2007); those modules are currently missing.

The inter-European and intercontinental trade in wood-based products and fuels is increasing, and there is a large potential for exporting wood products, or prefabricated wooden buildings, from forest-rich countries in northern Europe to other regions that predominately use brick or concrete construction. This would expand the energy and greenhouse gas benefits of wood construction further, decreasing total energy use and climate change impact. Nevertheless, our scenarios show that despite a large part of the growth of the forest stock being currently unutilized in Europe, an increase in the demand for wood products in Europe would also lead to higher imports from other parts of the world. However, we have not considered the potential for increased wood use outside of Europe. One should also recognize that not all measures to adapt forest management have been taken into account in this study.

The competitive position of the European forest sector is currently not very strong due to rather high production costs. Hence, in order to gain both the climate change mitigation benefits and economic benefits from increasing the use of wood as a construction material, promotional and technical efforts have to be taken in order to increase the use of wood from European forests. Various obstacles stand in the way of increasing the use of wood-based construction material. In Sweden, for example, the use of wood frames in multi-storey buildings was prohibited by law for over 100 years, during which time a path dependency favouring concrete construction developed (Bengtson 2003). Mahapatra and Gustavsson (2008) describe several criteria for the eventual emergence of wood-frame multi-storey building construction in Sweden, including investments in knowledge creation, incentives for entry of new firms and the formation of actor networks. The use of economic instruments to internalize the external costs of construction materials would increase the economic competitiveness of wood construction materials in relation to non-wood materials (Sathre and Gustavsson 2007, 2009). Taxation of fossil fuel use and/or carbon emission may act as an economic incentive to overcome organizational inertia, encouraging firms to adopt innovations that result in both lower environmental impact and increased economic benefits (Porter and van der Linde 1995). Still, the taxation of fossil fuel use and/or carbon emissions would have a minor influence on total construction cost (Sathre and Gustavsson 2009).

Wood building materials are part of a complex production chain involving forest managers, wood product industries, building constructors and end-users. The complexity increases further due to global market interactions and the inherently long time frame required for forest production. Numerous previous studies have quantified the greenhouse gas impacts of parts of the forestry—forest product chain. These studies have shown that various elements of the forest sector can each play a significant role in climate change mitigation efforts. In the present study, we have endeavoured to integrate quantitative models covering multiple parts of the forest sector to identify synergies and trade-offs among the various elements. We have identified several areas where this complex modelling framework could be improved. Nevertheless, the results of our integrated analysis corroborate the results of earlier studies, suggesting that increased use of wood in the construction sector will contribute to mitigating climatic change.

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